1 Introduction

Spread footings are generally preferred as foundations for structures when conditions permit. If the upper soils are weak and/or susceptible to scour and the structural axial/lateral loads are large, a deep foundation is typically recommended. Although many types of deep foundations are in use today, the most popular are driven piles and drilled shafts. Prior to selecting the type of deep foundation, the engineer must obtain sufficient information on the structural load transfer mechanism between the subsurface materials and the foundation. Historically, standard deep foundation design practices were simple with a large factor of safety for axial loads and serviceability (settlement) was typically not considered. Today, foundations are designed for much larger loads per element, and deformation/displacement calculations for both axial and lateral loading conditions are required. The effect of extreme conditions such as seismic activity, scour conditions, and vessel impacts are also included. Higher loads naturally result in less design redundancy within the foundation. Non-redundant deep-drilled shafts beyond 3-m diameter have recently been constructed on several bridges (Figure 1.1).

The implementation of drilled shafts as deep foundations for bridges has increased dramatically in recent years. A reason for this growth has been the advent of routine non-destructive evaluation (NDE) techniques. Drilled shaft performance, the ability to resist applied loads with an assumed safety factor, is not only dependent on the design but also on the quality of construction practices. All foundation elements must therefore be installed according to the design specifications without flaws. The use of outdated "routine practice" construction specifications and methods frequently produced undesirable situations during construction. Detailed routine inspection procedures by qualified inspectors during drilled shaft construction are essential but

Figure 1.1 Photo. 3m Diameter, 32m Deep Drilled Shaft Foundation for a Bridge Structure Located at State Highway 19 over the Missouri River at Vermillion, South Dakota.

may not be adequate in evaluating the final shaft integrity. Construction defects occurring during concrete placement in deep foundations are typically not obvious, and often result in structural stability or safety issues.

Recent research indicated that tremie poured concrete does not flow into the annular area as commonly thought in drilled shafts (Brown, 2003). Concrete flow through steel reinforcement is a behavior dependent on many characteristics. The relative size of the coarse aggregate in the concrete mix and the minimum space between reinforcement bars is one of the most relevant factors. The clear spacing to aggregate diameter ratio (CSD) is generally greater than 20. As the demand for larger capacity foundations increases, the shaft diameter and the steel amount in the rebar cage also increases. Recommendations call for a minimum cage spacing of 3 to 5 times the coarse aggregate to allow for free flow of concrete past the reinforcement into the annular area of the shaft (O'Neill and Reese, 1999). If the rebar cage has small clearance spacing due to high steel amounts, the following may occur: (a) sediment will settle out of the slurry and slough off to the side as concrete is poured, decreasing the bond between concrete and bearing strata; (b) voids in the concrete may be created outside the cage, reducing side resistance, and (c) concrete may not effectively flow into the annular area, and may create a void space, exposing steel reinforcement to ground water (Brown, 2003).

Defects are defined as zones in which the drilled shaft structural material or configuration has a lower load carrying capacity than originally designed. Defects in drilled shafts may be caused during drilling, construction, or casing, and may include soil intrusions, honeycombs, voids, and concrete mixed with soil or slurry. These anomalies or defects may produce other long-term weaknesses within the drilled shaft, such as exposing rebar to corrosion. Exposed rebar has reduced resistance to buckling or lateral loads, and thus reduces the life expectancy of the foundation. Current structural design methods for drilled shafts are inadequate because the presence of flaws is not considered. A substantial cost savings can be realized if foundation flaws are detected early, when repairs can be made.

Obtaining accurate and timely information on the integrity of concrete structures such as drilled shaft foundations is essential for project economy, progress, and success. In the mid 1980's, a campaign was launched intending to simulate the development of mobile, inexpensive, reliable non-destructive methods for assessing the quality of drilled shafts during construction (Litke, 2005). These NDE methods are increasingly being adopted for quality assurance on highway projects to assess the integrity of deep foundations and other civil engineering structures. Quality assurance and control for bridge foundations is essential for building a safe and long lasting bridge.

Present NDE methods do not yield absolute values of material physical properties, but measure geophysical dynamic properties that correlate to the material physical properties. Therefore, material modulus and strength within a structure can only be estimated based on the value of in situ geophysical measurements, creating justifiable concern about the accuracy of the results.

Cross-hole sonic logging (CSL), the most popular NDE method within state department of transportations, has been routinely used for several decades to characterize the integrity of drilled shafts. Although 3-D tomographic data acquisition and analysis has been recently applied, CSL technique is still hampered by uncertainty with respect to what specifically constitutes defective concrete. If CSL data provides accurate information on the geometry and location of defects in a drilled shaft, the structural loading capacity can be determined in 3 D modeling as discussed latter.

One fundamental problem is establishing an appropriate technical definition for what may be called "local average velocity (LAV)", which is used as the reference datum within a velocity log along the drilled shaft. The following general guidelines are presently used for rating concrete quality within deep foundations using velocity data from CSL results:

- Good/Acceptable concrete: 0-10% reduction (from "LAV")
- Questionable concrete: 10-20% reduction
- Poor/Not Acceptable concrete: >20% reduction

Obviously, from the above criteria, it is critical to calculate the "local average velocity" for each drilled shaft with some accuracy. Velocity deviations from the local average at any point along the drilled shaft are used as the measure to characterize the foundation integrity. If a drilled shaft contains several contaminated low velocity zones, the "local average velocity" is proportionally reduced, and therefore invalid concrete ratings may be produced.

Ultimately the question to be answered is not whether the foundation has defects (because defects or flaws are often unavoidable), but to determine the effects of defect frequency, geometry, and location on the structural performance of the drilled shaft foundation.

1.1 Purpose and Objectives

This research will mainly focus on the evaluation of the structural integrity of drilled shafts using the crosshole-sonic logging method. The research objectives are mainly to analyze the effectiveness of crosshole sonic logging (CSL) surveys to characterize the integrity and bearing capacity of deep-drilled shaft foundations. Numerical models will be constructed to isolate, control, and measure the effects of various phenomena.

A well-established, comprehensive numerical model based on the Particle Flow Code (PFC) method will be used for this research. PFC is a Discrete Element Method

(DEM) that uses combinations of small spherical elements bounded by springs of various stiffness to model the larger, more complex elements commonly used in DEM. This modeling method was selected because it supports solids, with effects of friction, interlocking, collisions, and cracking, as well as fluids and solid/fluid interaction. This method also has the capability to model dynamic crack propagation, seismic waves, and static loading in concrete, soil, and other geotechnical materials. The PFC method was also expanded to model a wider range of phenomena, such as concrete curing, heat transfer, thermal cracking, honeycombing, surrounding ground conditions, ground water effects, and corrosion.

This study will simulate CSL surveys under various conditions commonly encountered in the field. The effect of the following factors on velocity propagation will be examined:

1. Access tube-- including tube bending, sensor drift and orientation within the tubes, steel versus PVC tubes, thermal expansion during concrete hydration, and tube debonding.
2. Rebar--including CSL signal reflection and dispersion, rebar thermal expansion, and rebar debonding.
3. Concrete hydration in typical ground conditions and at different curing times, using chemical hydration rates, heat transfer, and thermal stress.
4. Common defects will be introduced into the models, such as honeycombing, soil intrusion, and thermal cracking. Simulated CSL surveys will be evaluated for effectiveness to detect and classify these defects using simulated waveform analysis.

Next, numerical stress analysis will be performed on defects within the drilled shaft to estimate effects on bearing capacity and structural integrity.

The purpose of this study is to explore the potential to process full-waveform seismic data collected from existing survey techniques to obtain a more accurate and comprehensive estimate of drilled shaft performance and structural integrity. The evaluation of steel corrosion in the drilled shaft is also of importance since it may reduce the design life of the drilled shaft.

1.2 Background-Drilled Shaft Foundations

Since this research is mainly focused on the evaluation of drilled shafts with defects, this section will provide a brief overview of drilled shaft design and construction, advantages and disadvantages, and construction inspection and observations methods.

1.2.1 Description

Drilled shafts are cast-in-place deep foundation support elements constructed by drilling a cylindrical hole, lowering a structural steel rebar cage into the hole, and then filling the hole with concrete. There are numerous methods and problems associated with each method in completing each of these three steps. The geological environment influences the appropriate course of action to create a reliable structural element. Drilled shafts are typically capable of supporting high, concentrated loads. Drilled shafts are the foundation of choice for heavily loaded, seismically sensitive structures, because of their ability to resist axial and lateral loads. However, sensitivity in construction practice is important for successful implementation of this type of foundation.

Drilled shafts, also referred to as "drilled caissons", "drilled piers", "cast-in-drilled-hole piles", and "bored piles", typically range from 0.5 to 4-m in diameter and can be placed at depths up to 50 m. Several factors influence the ratio of depth to diameter (L/D), such as the nature of the subsurface soil profile, the groundwater table level, whether or not a rebar cage is required, the concrete mix design, and the lateral support requirements. Typically the aspect ratio of drilled shaft, its length divided by its diameter, is less than 30 (L/D < 30). Available drilled shaft construction equipment is capable of drilling cylindrical holes up to 6-m in diameter, to depths of up to 75 m.

Depending on subsurface soils and design load conditions, the diameter at the base of the shaft may be increased (belled) up to three times the diameter of the shaft to increase base resistance. Structural loads are supported by base resistance, side resistance, and existing bedrock, if accessible. A typical schematic of drilled shaft construction with loading is shown in Figure 1.2, and a typical drilled shaft construction operation is shown in Figure 1.3

Drilled shafts are constructed straight, belled, and rock-socketed using two different methods:

- Dry method – construction of a shaft without water interference. The dry construction method consists of drilling the shaft excavation, removing loose material from the excavation, and placing the concrete in a relatively dry excavation. Casing may be used as temporary or permanent; the temporary casing construction method is normally used when excavations in the dry construction method encounter water bearing or caving soil formations. A temporary casing is placed into the impervious formation to produce a watertight seal at the bottom. The casing is withdrawn during concrete placement. The permanent casing method consists of placing a casing to a prescribed depth before excavation begins. If caving or water bearing soils are encountered during dry drilling, the hole is filled with water and drilling advances the excavation.

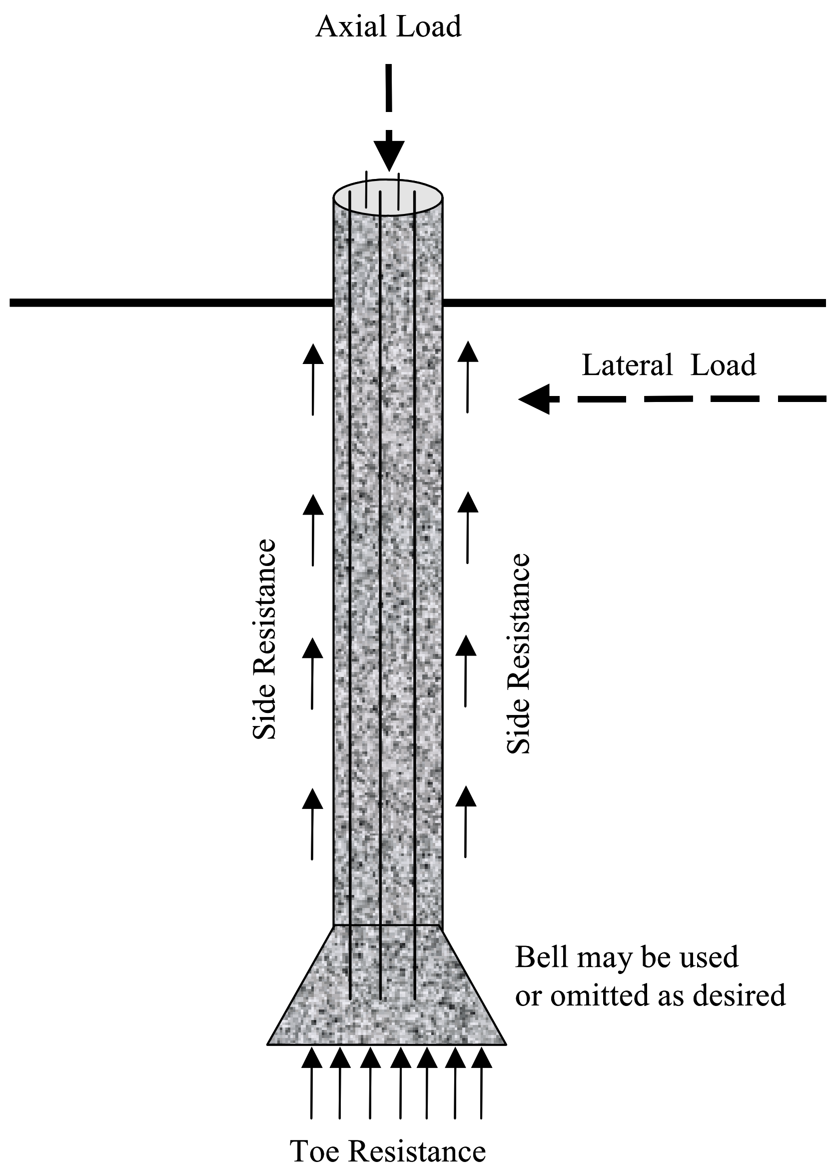


Figure 1.2 Schematic Diagram of a Typical Drilled Shaft Foundation.

Figure 1.3 Photo Showing Drilled Shaft Construction

- Wet or slurry methods – constructing a shaft either with ground water or under water using tremie concrete. In this type of operation, drilling slurry (typically commercial bentonite clay mixed with water) or polymer slurry is used to stabilize the excavation, or to prevent inflow when ground water is encountered in the excavation that cannot be dewatered.

Typical problems that may be encountered during construction, such as hole caving, casing advancing and retreat, dewatering, and obstructions, can best be evaluated by drilling a full size test shaft during the exploration or design phase of the project.

If this is not feasible, the geotechnical engineer must include an advisory on the potential problems that may be encountered during shaft construction. Some subsurface conditions affecting construction procedures are:

- Soil stability against caving or collapse: Test holes are drilled to determine the need for casing during construction dry method should only be allowed in non-collapsible soils.
- Groundwater elevation and water inflow rates (artesian water conditions): These should be estimated to indicate if dewatering is needed and determine the method of concrete placement to be used.
- Bedrock elevation or large boulders: If these are expected along the axis of the drilled shaft, specialized drilling equipment may be required and included in the estimate.
- Weak soil layers just below the base of the shaft: For this condition, drilling may have to extend below the weak strata.

1.2.2 Advantages and Disadvantages

The use of drilled shafts as deep foundations has several advantages and disadvantages over driven piles and smaller diameter pre-stressed concrete piles.

Advantages:

- Drilled shafts can be constructed in soils with cobles and boulders, and can be drilled in rock.
- Mobilization/demobilization costs are generally less, especially if the foundations are a small part of the project.
- Subsurface soils can be examined during the drilling.
- Drilled shaft diameter and length can easily be altered in the field if different soil conditions are encountered than anticipated.
- The structure can be supported on one large diameter column instead of several piles.
- Drilled shaft construction generates less noise and pollution, and is favored in urban areas and where environmental concerns are an issue.
- Drilled shafts have better resistance to large lateral loads such as wind, and better resistance to lateral impact from ships or vehicles.
- Drilled shafts are easier to install in regions with shallow rock.
- Lower impact when right-of-way constraints are an issue.
- Improved economy because each shaft replaces a large numbers of piles and pile caps.

Disadvantages:

- Drilled shafts are highly dependent on contractor experience and workmanship. Quality control is not easily performed after construction. If defects occur during construction, they are not seen and may cause a poor foundation that is unable to support design loads. This is important, especially if only one or two drilled shafts are used.

- When soil is excavated during drilling, the existing ground lateral are reduced therefore drilled shafts generally have less soil frictional capacity than driven piles. The concrete/soil friction may sometimes accommodate this loss.
- Pile driving increases the density of the soils beneath the tip, whereas shaft construction does not. Lower bearing capacity at the toe results from the removal of soil during drilling.
- Drilled shaft capacity testing is expensive and is normally only used on larger projects with many shafts.
- Defects during construction are difficult to detect without the aid of non-destructive methods.
- If the drilled shaft is constructed in slurry, concrete contamination may occur during concrete displacement of the slurry, reducing concrete strength.
- Occasionally, soils may cave into the drilled shafts during construction.

1.2.3 Construction Inspection and Observation Methods

During construction, full time inspection of drilled shafts by qualified personnel is a necessary part of the process. Inspection observation methods such as probes, video camera inspection, remote shaft wall inspection devices, or various calipers are not suitable substitutes for routine "topside" construction inspection. Remote or indirect observation methods are valuable alternatives to direct entry of personnel into drilled shaft excavations. They should be considered whenever appropriate to reduce the risks associated with direct entry of personnel.

Observations made during construction are essential for quality construction of drilled shafts. The shaft depth, diameter, plumbness, bottom conditions, reinforcement, concrete continuity, and bearing conditions are most easily checked during construction. Some of these observation methods include excavation around the shaft for relatively shallow inspection, down-hole inspection for end bearing conditions or rock sockets, and video camera devices for remote inspection. In rare circumstances it is justifiable to create a test drilled shaft that can be extracted for inspection. Before concrete placement, the bottom of the shaft can also be probed by drilling or coring to determine if there are voids or soft zones in the material at the base of the shaft.

This summary focuses on traditional "topside" inspection for routine drilled shaft construction. However, recognizing that "down-hole" inspections are still sometimes performed, this summary provides guidance to the inspector (and geotechnical engineer) on technical considerations for such inspections. Federal safety regulations for entering shafts are promulgated by OSHA. Individual states, owners, or contractors may have additional regulations.

1.2.3.1 Down-Hole Inspections

Down-hole inspections by qualified personnel provide an opportunity to determine the condition of the bearing stratum of drilled shafts, and provide guidance to the geotechnical engineer and inspector about the technical conditions to observe and note. Direct down-hole observation provides the best opportunity to view and manually explore end bearing conditions and/or rock socket with a geologist's hammer, pocket penetrometer, or a short manually pushed, thin-wall sampler. Samples can be obtained and preserved. Shaft walls in earth cannot safely be observed because of the need for protective casing to enter the shaft.

1.2.3.2 Probe Inspection

It is sometimes necessary to probe below the bottoms of drilled shafts to determine if there are voids or cavities that will interfere with the load carrying capacity. This step is often necessary for rock sockets in limestone and dolomites or for drilled piers carrying very high loads. The procedure is usually to core a 50 or 75-mm diameter hole about 1 to 3 m below the excavated bottom of rock socket using an air-track rig. For elements founded in soil strata, pre-construction borings at each shaft location are sometimes recommended.

1.2.3.3 Video Camera Inspection

Video camera inspection of drilled shafts is increasingly common for shafts that are either inaccessible, constructed over water, or where direct entry by personnel is not desired. Certain video systems can be used in shafts constructed with slurry. The video camera system provides real-time images, as well as a videotaped record, of the shaft walls and bottom conditions. While different procedures for videotaping the shaft walls are used, an efficient method begins at the bottom of the casing by performing a 360° rotation around the shaft, lowering the camera a fixed distance (300 mm), and performing another 360° rotation at that level. The procedure is repeated until reaching the bottom of the shaft. The camera angle is changed to view the shaft bottom. A weighted engineering tape, fixed at the north edge of the shaft wall, can provide a convenient depth and azimuth reference. The miniaturization of cameras has allowed smaller shafts to be inspected.

The greatest advantage of video camera inspections is that they avoid the need for entry of personnel into shafts. The camera provides a real time view, allowing the geotechnical engineers at the surface to evaluate the shaft during the inspection. A permanent videotape record allows later viewing as well. The camera provides observation in inaccessible small diameter shafts, shafts under water, or shafts constructed with slurry. The disadvantage is that the video camera provides only a visual image, without opportunity to physically sample or probe the shaft.

1.2.3.4 Shaft Wall Sampling and Rock Socket Wall Roughness Inspection

The wall roughness of rock sockets have become of interest, as research shows a correlation between wall roughness and side shear capacity in certain types of bedrock, such as shale and mudstones. Some shaft designs call for grooves to be cut in the walls or rock sockets and drilling tools that cut grooves are commonly in use.

A shaft wall sampler is a device lowered into a drilled shaft excavation that is capable of remotely retrieving a small sample of the shaft sidewall. This device can obtain small diameter "tube" samples of soils or soft rock from the sidewall of a shaft at any depth. The samples can be extruded and used to observe the magnitude and rate of slurry cake buildup, rate and magnitude of sidewall softening, and for evaluation of sidewall strength. Samples of cohesive soil can be tested for comparison to strength parameters used during design.

A more sophisticated "shaft inspection device" may also be used, which includes remote socket wall sampling, a video camera, calipers for measuring the diameter of the shaft and a probe that can measure the thickness of sediment on the bottom of the shaft.

Like video camera inspections, these devices offer the advantage of "topside" operation without risk of personnel entering the shaft excavation. For shafts constructed under water or with slurry, these methods and equipment offer capabilities for down-hole inspection testing that are not otherwise currently available.

The roughness of the wall of a rock socket can vary substantially, depending on rock type, jointing, rock strength, drilling tools, drilling technique, presence of a roughening tooth, and roughening technique. A down-hole laser-based measurement device has been developed for precise measurement of socket-wall roughness. The equipment may be used in sockets greater than 600 mm in diameter. The precision of socket-wall roughness measurements is within 2.5 mm. In addition to confirming the size and location of grooves, this device also provides a detailed vertical profile of the sidewall, including asperities and vertical angularity.

These devices also offer the advantage of operation from "topside" without risk of personnel entering the shaft excavation. For shafts constructed under water or with slurry, they offer capabilities for measuring the roughness of a rock socket that are not otherwise currently available.

1.2.3.5 Electro-Mechanical and Acoustic Shaft Caliper

Shaft calipers are lowered into a shaft excavation from the ground surface to measure the gross diameter or shape of a drilled shaft excavation. Typically, calipers are used in shafts excavated under water or with the slurry method, although they can also be used in dry holes. A chief objective is to check for necking, squeezing, or zones of caving in drilled shafts that are in soil. Obviously, calipers cannot be used in shafts with either temporary or permanent casing. They are also less important for rock sockets made in competent rock formations.

The two main types of shaft calipers are electro-mechanical and acoustic. Electro-mechanical shaft calipers were developed for monitoring oil well drill holes. The devices can be operated in dry shafts, or shafts completely or partially filled with water or slurry.

The devices are typically four-pronged, spring-loaded steel "feelers," much like the feeler rods in a pressure meter, only much larger. The radius value is calibrated to the feeler rotation, which is measured by an electrical potentiometer. The precision of this device is approximately 6 mm radially and 1 mm in depth. The maximum sized hole diameter that can be measured with this precision is about 2 m.

An alternative and increasingly common method of shaft inspection is by acoustic methods. Acoustic methods require a fluid (water or slurry) for signal transmission, as acoustic calipers only function when submerged. An additional benefit of these systems is that verticality of the shaft can also be assessed.

Although specific features of different devices vary, the acoustic calipers use one or more radial-spaced ultrasonic transducers to transmit and receive acoustic signals between the sensor and the borehole wall. The diameter of the borehole is measured at a rapid rate while the caliper is lowered. The sensor usually incorporates a magnetometer and an accelerometer, which are used to directionally orient the caliper data. This information can then be used to provide a three-dimensional model of the shaft cavity. Results are provided in real time and in digital form.

Similar to video camera inspections, shaft calipers offer the advantage of operation from "topside" without risk of personnel entering the shaft excavation. For shafts constructed under water or with slurry, they offer capabilities for measuring the diameter of a drilled shaft that is not otherwise currently available.

1.3 NDE Methods for Determining Drilled Shaft Integrity

NDE techniques are used with the expectation of replacing expensive and potentially destructive full-scale static and dynamic load testing techniques. However, when disputes arise over questionable NDE results, full-scale load testing may be required to avoid lost time and/or legal costs. As understanding and trust in NDE increases, situations requiring reliance on full-scale testing can be reduced. This section will provide an overview and the history of the development of NDE methods for use as QA/QC tools during drilled shaft construction. A summary of results is included from a recent comprehensive synthesis conducted under an FHWA contract to the knowledge and applicability of NDE methods within the State DOT's. The survey results indicated that the majority of responding states use crosshole sonic logging as the primary NDE method for characterizing drilled shaft integrity.

Several widely used methods including sonic echo, impulse response, gamma-gamma density logging, crosshole sonic logging, and other methods are briefly described. Since the main focus of this research is on CSL data and results, a more detailed discussion of this method will be provided.

1.3.1 Overview

Geophysical non-destructive evaluation techniques have long been accepted in the petroleum, mining, and metallurgical industries. Over the past century, many imaging techniques have been developed using methods such as X-ray, acoustic/sonic energy, radar, infrared, electrical/electromagnetic, and nuclear. These methods are conducted either from the surface or using downhole probe technologies. Cross-hole logging, an acoustic technique, has its roots in petroleum exploration, and has been through several phases of development. Electrical logs were first introduced in the 1920's to identify oil-bearing formations. By the mid-1940's, electronic downhole systems were in use. During this era, the widespread deployment of electromagnetic, acoustic, and nuclear logging systems, including the use of gamma-density and neutron-porosity probes, was seen. These logging systems were developed mainly to comprehensively characterize reservoir conditions by measuring water (versus. oil or gas) saturation, formation porosity, and permeability.

1.3.1.1 History of Non-Destructive Evaluation Methods

The first sonic probe logging system was introduced in the 1950's and consisted of a single acoustic source and two in-line receivers. The second-generation sonic probe was initiated a decade later and consisted of a source with multiple pairs of receivers to compensate for borehole effects. These systems became popular for mining applications, including exploration of base metals and uranium, for shallow (<1,000 m depths) oil and gas applications, and civil and environmental engineering applications. The engineering applications included logging for geotechnical, ground water, hydro-geological, geo-environmental, and other environmental engineering objectives.

Pacquet and others originally researched downhole sonic logging for concrete evaluation in the early 1970's at the Experimental Center for Research and Studies in Building and Public Works in France. This led to the development of the cross-hole sonic logging (CSL) and gamma-gamma density logging systems for deep foundation quality assurance (Stain, 1982). Prior to the mid-1980's, quality assurance integrity testing of drilled shafts was mainly performed using the Sonic Echo (SE) and Impulse Response (IR) seismic test methods (Koten and Middendorp, 1981; Davis and Dunn, 1975). These seismic methods required only one free surface. However, such methods detect only large defects, generally with cross-sectional area change greater than 5%, and only work properly on drilled shafts with maximum length-to-diameter ratios of 20:1. Smaller defects located below a major defect are shadowed and may not be identified. The type of soil in which the shaft is embedded limits the penetration of the seismic signal.

The drawbacks associated with the SE and IR methods, recent advancements in PC-based digital signal recording and processing, and better understanding of the physical factors affecting test performance have resulted in development of the current cross-hole logging methods using both ultrasonic and nuclear sources. Recently, cross-hole sonic logging has become the standard method for characterizing concrete structure integrity in drilled shaft foundations. CSL tests provide information about concrete integrity by transmitting an ultrasonic signal from a tube, through the structure, and receiving the signal in an adjacent tube. This test is usually conducted with the transmitter and receiver at the same horizon, but may be

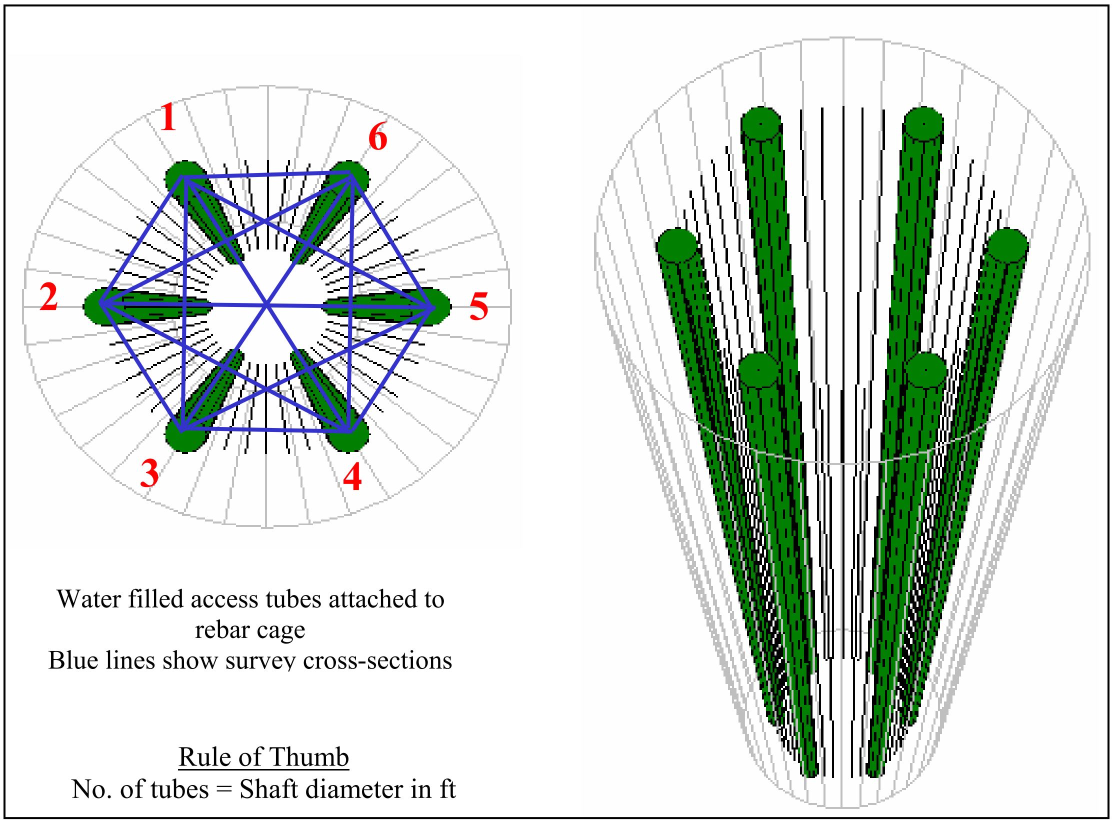


Figure 1.4 A Schematic Showing the CSL Setup

conducted with a predetermined vertical offset between the probes. This offset distance is limited by the signal power level and frequency used during testing. CSL access tubes are usually 50 mm in diameter and are securely tied to the rebar cage in a vertical orientation before shaft construction. The number of tubes required is determined from the diameter of the drilled shaft (Figure 1.4).

Although this method has proven to be valid, the results are generally difficult to interpret and were therefore often ignored by the project site engineer. Recent studies have shown that refining CSL data presentation with color-coded 3-D images vastly improves concrete pier integrity characterization and is more likely be used by the project site engineer, ultimately minimizing risk and reducing cost.

1.3.1.2 Summary of a National DOT Synthesis on Use of NDE Methods

NDE practices varied considerably from state to state. Some states have minimal experience with these methods while others use NDE on all drilled shafts. A synthesis was conducted by California State University (Tufenkjian, 2003) to determine the current and future application of NDE methods for evaluating drilled shaft integrity among state DOTs. The survey questions were developed in parts, aimed at determining how many transportation agencies use NDE for testing drilled shafts, the level of experience that they have in these methods, and the types of NDE methods most implemented in their state. About 44 out of the 50 (88%) of the State Department of Transportations participated in the survey (Figure 1.5), 43 states (98%) reported using drilled shafts for deep foundation.

As with any statistical data, it is important to use caution when drawing conclusions from the data. A state responding to the affirmative could potentially use drilled

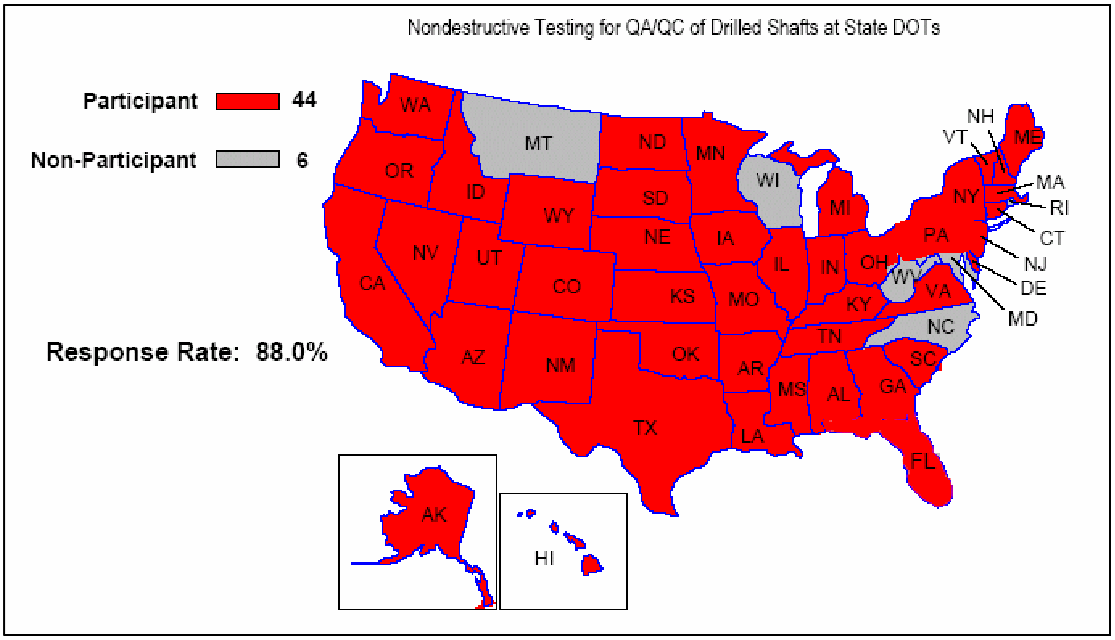


Figure 1.5 State DOT Survey Participants

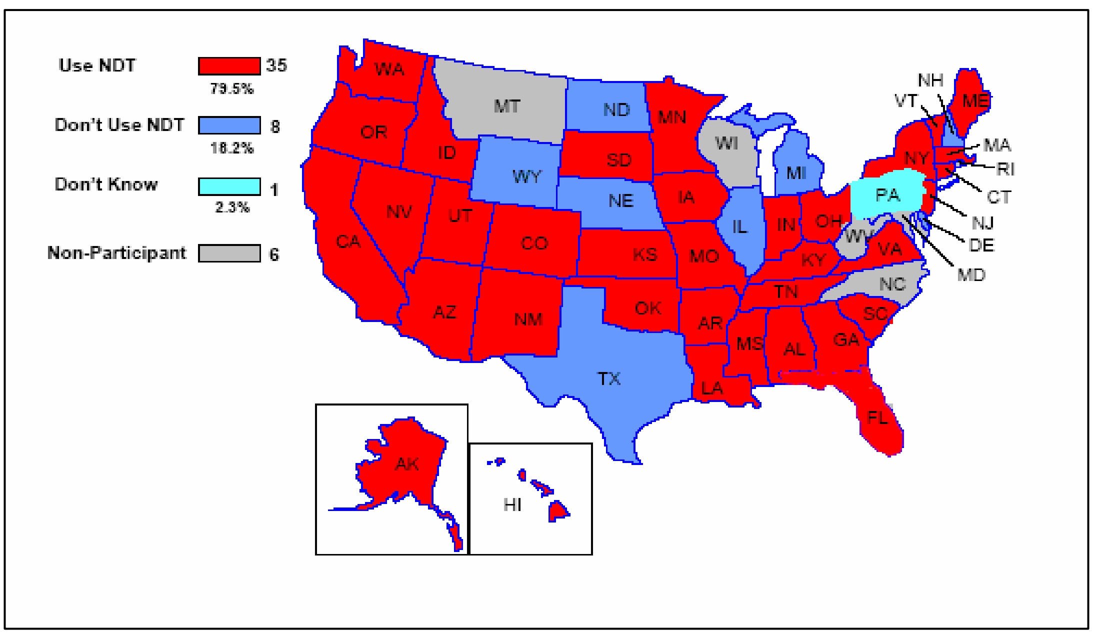


Figure 1.6 Map Showing the Responding State DOTs that Use NDE for QA/QC of Drilled Shafts

shafts only on a single bridge. Regardless, the survey does indicate widespread familiarity with drilled shafts.

Of the 44 respondents, a majority of 35 states (80%) reported using NDE techniques routinely for quality assurance and quality control on drilled shafts (Figures 1.6 and 1.7).

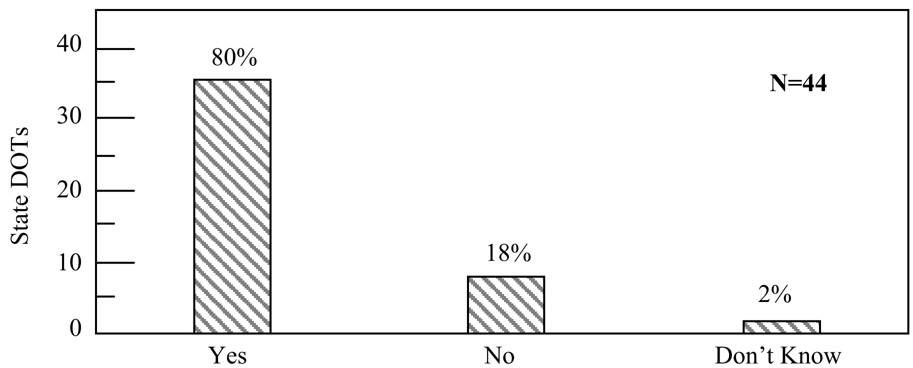


Figure 1.7 The Survey Results for the Question; "Does your state DOT use NDE for QA/QC of drilled shafts?"

When asked if their state uses other quality assurance verification procedures, 80% responded positively. The overwhelming alternative procedure mentioned by the responding states was drilled shaft coring followed by load testing using conventional means, or by use of an Osterberg load cell. Only 36% indicated that they were "very familiar" with NDE methods, while 64% indicated that their state was "somewhat familiar" with NDE methods for testing drilled shafts. Almost all responding states (93%) indicated the need for additional training.

When asked which NDE method is the primary method used by the state DOT, the answer was consistent with the literature, where the overwhelming majority of 33 out of 35 states (94%) that use NDE responded that the crosshole sonic logging method was the primary method used (Figure 1.8). Only Caltrans indicated that they use the gamma-gamma method as the primary method, and if defects are detected, they apply the crosshole sonic logging method as a secondary method for verification. Although sonic echo does not require installation of tubes and is quicker and cheaper to perform, it is surprising that only one state responded that they use this method as the primary NDE test.

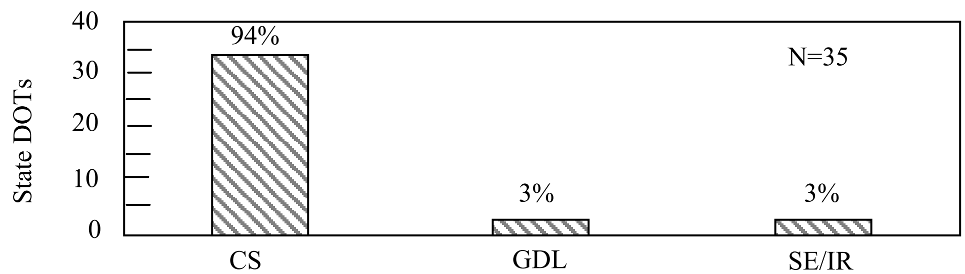
Over half of the states that use NDE indicated that CSL was primarily chosen out of familiarity with the technique, and not for any other reasons or requirements. The vast majority (83%) of the states using NDE were satisfied with the effectiveness of the method, while 14% were not satisfied. Of those who were not satisfied, the common explanation was that a standard or an acceptance criterion had not been established, or that the NDE results were highly subjective and open to interpretation. About half of the states specify non-destructive evaluation for drilled shafts under slurry only, and one third indicated that all their drilled shafts constructed with temporary casing for caving control are specified for testing. Only 17% of the respondents indicated that all their drilled shafts are tested regardless of conditions.

A majority of the states also indicated that very few imagery or calibrations are done in the shaft prior to concrete placement for quality control measures.

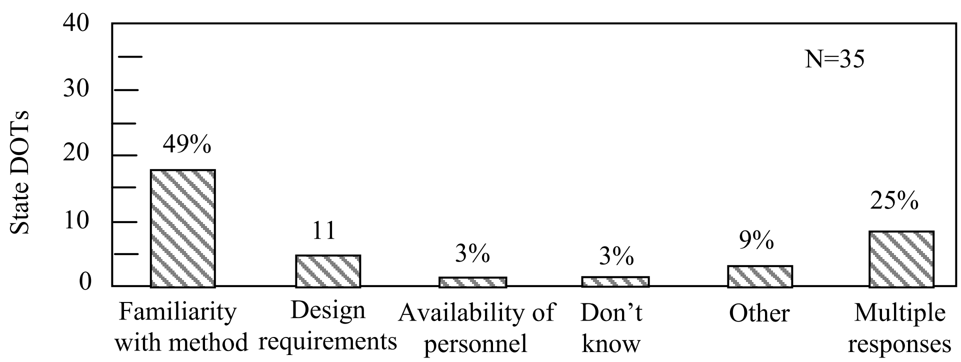
1.3.2 Sonic Echo and Impulse Response (SE and IR)

These methods are sometimes referred to as pile integrity methods. Additional names for the sonic echo method include echo seismic and pulse echo. Other names for the impulse response method include sonic mobility, transient dynamic response, impulse response spectrum, transient response, and transient dynamic response.

These techniques are relatively inexpensive, and sophisticated test equipment is not required. These methods are more commonly used to evaluate existing shafts, pre-cast driven concrete or timber piles, and auger-cast piles than newly constructed shafts. Their use during construction is typically to confirm results from other NDE tests if required. These techniques have also been used on shallow concrete structures such as wing walls, provided the top of the wall is accessible. SE and IR tests are generally performed to approximate the length of deep foundations, to detect anomalies, soil inclusions, pile necking, and shaft diameter bulging.



(a)



(b)

Figure 1.8 Survey Results for the Questions a) Which is the primary NDE method your state uses for drilled shafts and b) What is the main reason your state selects the primary NDE method?

1.3.2.1 Basic Theory and Procedures

Sonic echo and impulse response test equipment simply require a small hand-held impulse hammer with a built-in load cell, and an accelerometer. During the test, the top of the shaft is struck with the hammer, creating a downward traveling compressional wave. The generated wave typically travels down the shaft until a change in acoustic impedance (depending on variations in velocity, density, and/or shaft diameter) is encountered, where the wave reflects back and is received by an accelerometer placed next to the impact point, as illustrated in Figure 1.9.

The same data is collected for both types of tests. These data are analyzed in the time domain for the SE method, and in the frequency domain in the IR method. SE signals are integrated to produce travel time velocities, and may require the application of a gain function or sophisticated signal processing techniques to enhance weak reflections and compensate for energy damping.

The tests for SE are typically performed with different frequency filters to optimize reflections from the foundation toe, and to reduce the effect of surface waves or reflections from a discontinuity at a shallow depth, which result in higher frequencies. In an IR test, a digital analyzer automatically calculates the transfer and coherence functions, after transforming the time records of the hammer and the receiver to the frequency domain.

For drilled shafts, the best results from SE/IR tests are obtained if the top of the drilled shaft is exposed to allow receiver attachment and hammer strikes as illustrated in Figure 1.9a. If, however, the top of the shaft is not exposed, the test can be performed on the side, providing at least the upper 300 to 600 mm of the shaft is exposed (Figure 1.9b). In cases where the superstructure is in place, the SE/IR data is more difficult to interpret because of the many reflecting boundaries, and multiple accelerometers may be required.

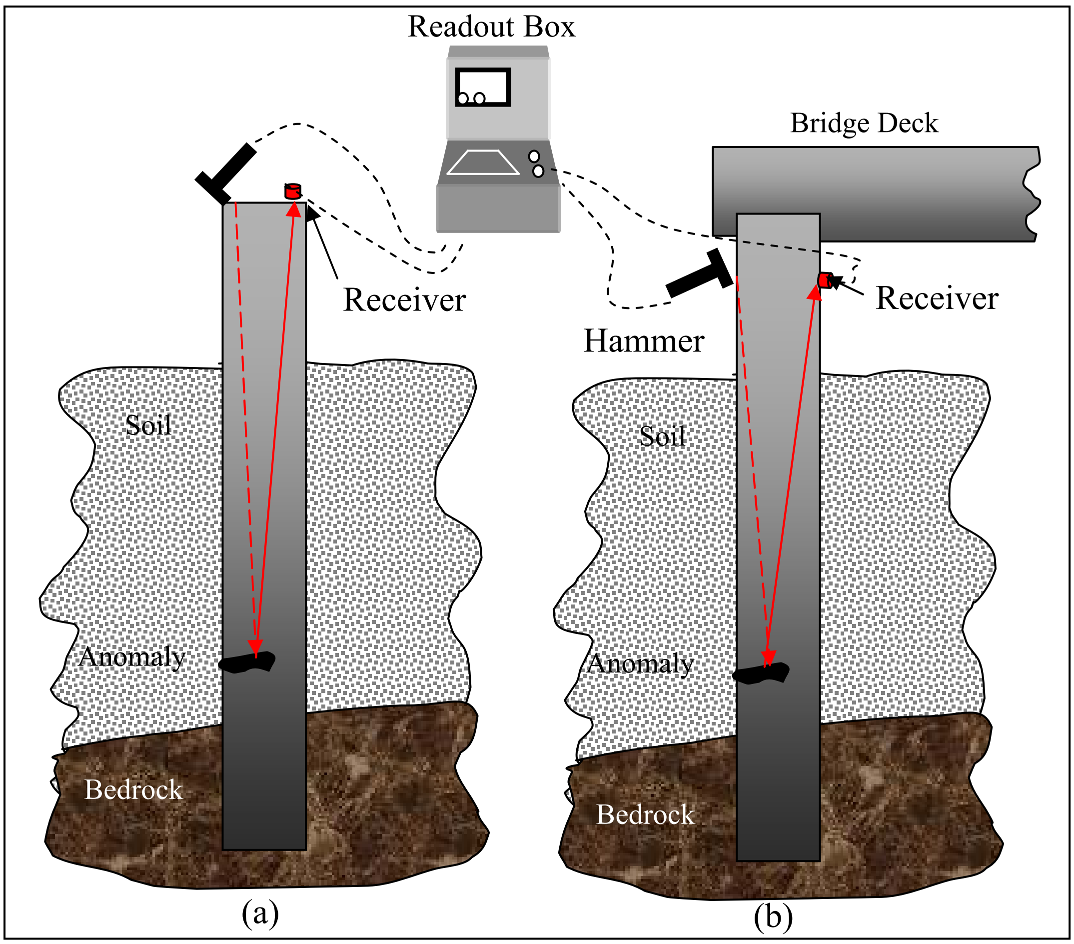


Figure 1.9 Sonic Echo and Impulse Response Equipment and Setup.

For accurate results, it is important to also measure the P-wave velocity of the concrete in the tested structure. It is not reliable to assume concrete velocity or to measure it in the laboratory using ultrasonic pulse velocity tests. Concrete velocities vary based on the mix, aggregate size, structure age, state of weathering, or other degradation. Local velocity can be easily measured if two sides of the structure of a sufficient length are exposed. A source placed a known distance from a receiver can be used to obtain a first arrival signal for computing the P-wave velocity.

1.3.2.2 Applications/Limitations

Sonic Echo data are used to determine the depth of the foundation based on the time separation between the first arrival and the first reflection events, or between any two consecutive reflection events (Δt) according to the following equation:

$$D = V \times \frac{\Delta t}{2}, \tag{1.1}$$

where

D is the reflector depth, and V is the velocity of compression waves.

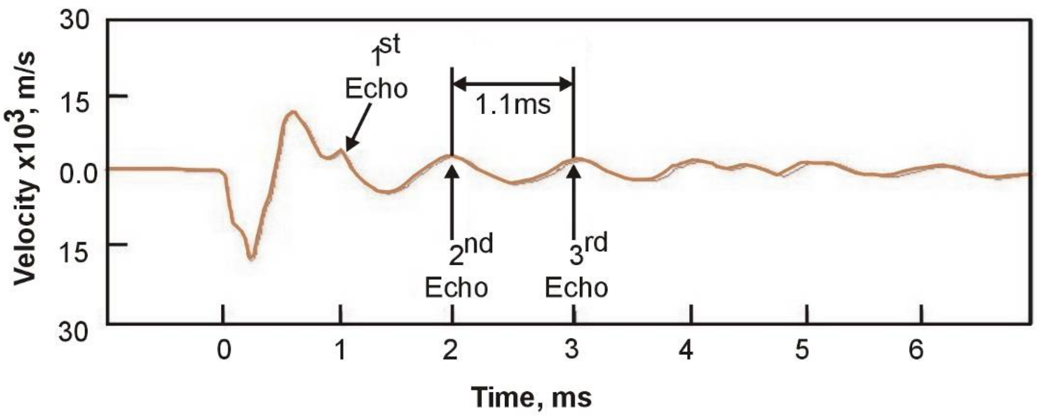
Figure 1.10 shows a sonic echo record and the depth calculation using the second and third echoes. The multiple echoes are all interpreted as coming from the same reflector since they are spaced equally in time. Any pair may be used to calculate the two-way travel time between the source and the reflector. The second and third echoes appear to be the clearest pair in the figure.

A reflector from the bottom of the Sonic Echo data can also be used to determine the existence of a bulb or a neck in a shaft, or indicate end conditions of the shaft based on the polarity of the reflection events. Impulse Response data are used to determine the depth of reflectors according to the following equation:

$$D = \frac{V}{(2 \times \Delta f)}, \tag{1.2}$$

where

Δf - the distance between two peaks in the frequency spectrum plot (velocity/force versus frequency) or between zero frequency and first peak for soft bottom conditions.



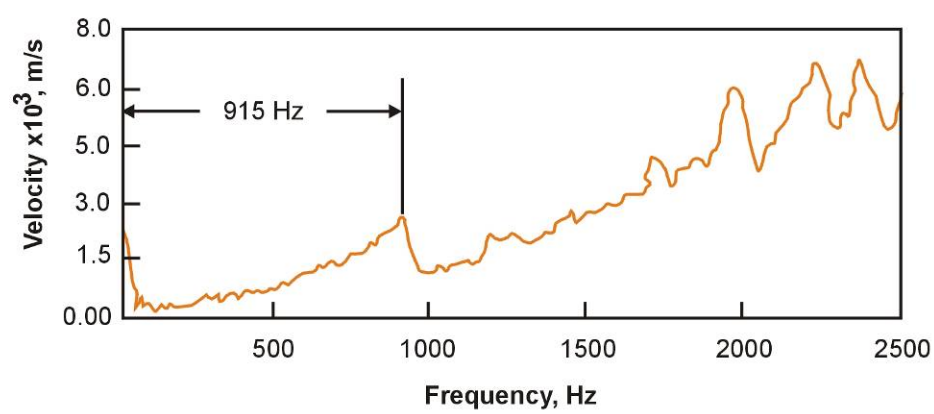
Depth = V xΔt/2 = 3,652 x 1.1 x 0.001/2 = 2.01 m

Figure 1.10 Sonic Echo Record and Depth Calculation

The multiple echoes from a discontinuity or the bottom of the shaft, as seen in the sonic echo method, result in increased energy at the frequency of the echo. This causes a peak in the frequency spectrum. Under conditions where there is a hard material beneath the structure, the second harmonic of the echo is also evident. Using the frequency difference between zero and the main echo frequency or between the first and second harmonic frequencies in the above formula gives the depth of the structure. IR data also provide information about the dynamic stiffness of the foundation. This value can be used to predict foundation behavior under working loads or correlated with the results of load tests to more accurately predict foundation settlement. Example data for the impulse response method is shown in Figure 1.11, along with the depth calculations.

The SE/IR method works best for free-standing columnar-shaped foundations, such as piles and drilled shafts, without any structure on top. Typically, SE/IR tests are limited to shafts or piles of length-to-diameter ratios of 20:1. Higher ratios (30:1) are possible in softer soils but are not generally recommended. The method can only detect large defects with cross-sectional area change of greater than 5%.

A toe reflection is not possible if the pile is socketed in bedrock of similar dynamic stiffness (or acoustic impedance) as concrete. If the pile is embedded in very stiff soils, signal penetration may be limited to 7.5 m. For the softer soils, echoes can be observed from piles of up to 75 m in length. This method cannot be used for steel H-piles.



Depth = V/(2 x△f) = 3,652/(2 x 915) = 1.98 m

Figure 1.11 Depth Calculations Using Frequency Domain Data for the Impulse Response Method

1.3.2.3 Testing Equipment

The testing equipment consists mainly of a hand-held hammer and one accelerometer. The hammer is equipped with a trigger that is connected to a data acquisition system on which the seismic reflection data received by the accelerometer is stored and processed.

1.3.2.4 Defect Definition

The SE and IR methods are sensitive to changes in the shaft impedance and can identify the location of an irregularity or soil intrusion, but cannot accurately determine the size of the defects. Small defects can only be detected if larger ones above them do not shadow them. This shadowing effect is eliminated by downhole methods such as crosshole sonic logging or gamma-gamma density logging.

1.3.3 Gamma-Gamma Density Logging (GDL)

The 4-pi gamma-gamma density logging method was developed specifically for integrity testing of concrete foundations. Unlike crosshole sonic logging tests, GDL tests can be effective even when the access tube is slightly debonded from the concrete. Tube-debonding may have minimal affects on the results. Since this method utilizes a nuclear source, in state licensing and special handling permits are required to operate this system.

1.3.3.1 Basic Theory and Procedures

In GDL, a weak Cesium-137 (radioactive) source emits gamma rays into the surrounding material. A small fraction of the gamma ray photons are reflected back to the probe due to Compton scattering. The intensity of the reflected photons is measured and recorded by a NaI-scintillation crystal as counts per second (cps). The measured cps is dependent on the electron density of the surrounding medium, which is directly proportional to the mass per unit volume of the tested medium. The GDL instrument is generally calibrated in a test block constructed of the same concrete mix, with an access tube of the same material (PVC or steel) as those used in the structure to be tested. This will provide direct correlation between gamma intensity (measured cps) and concrete density (g/mm^3).

This downhole logging technique is generally performed using air or water-filled PVC access tubes attached to the rebar cage in the foundation prior to concrete placement. Steel tubes have also been used with GDL tests. It must be recognized, however, that the thicker or denser the tube material, the lower the measured counts per second (cps), since the tube itself absorbs some of the electrons.

1.3.3.2 Applications/Limitations

In the GDL test, the radius of investigation is largely governed by ½ of the source-detector spacing in the instrument. Source-detector spacing up to 350 mm are commonly used. The tests are performed in all tubes to obtain data around the perimeter of each tube. Good concrete will result in a near continuous alignment of the data. Anomalous zones due to soil intrusions, poor concrete, or voids are characterized by a high cps, indicating low density.

An obvious disadvantage of the method is the limited depth of penetration. This technique is not suitable for detecting large anomalies inside the reinforcement cage, but only along the outer perimeter of the shaft. Typically this method allows for soil intrusions or other anomaly characterization at a maximum radius of about 180 mm from the center of the tube. The location and geometry of the defect within the shaft cannot be determined, only its existence and depth. Combining CSL with gamma-gamma density method could provide a good complement.

1.3.3.3 Testing Equipment

Figure 1.12 shows the equipment used for gamma-gamma logging. Current equipment is based on lightweight geophysical logging systems that use a laptop computer for computer control, data acquisition, and storage. One person can operate this equipment.

Data processing is conducted with a microcomputer similar to that used for acquisition. The data are usually processed for bulk density. These calculations are preformed during real-time data acquisition or post-acquisition with a software analysis package.

1.3.3.4 Defect Definition

Variations in backscatter intensity are indicative of density variations within the drilled shaft. The GDL technique is therefore able to detect drops in average bulk density, indicating flaws in the material surrounding the access tube.

A typical GDL log is shown in Figure 1.13. This figure shows the GDL data from all access tubes plotted in unit weight versus depth from a drilled shaft, and a photo of the exposed upper portion of the shaft. Each plot also displays three vertical lines representing 1) the mean (M), 2) mean minus two standard deviations (M-2SD), and 3) mean minus three standard deviations (M-3SD).

The GDL results are used to define "questionable" concrete conditions as a zone with reduction in unit weight between 2SD and 3SD, and a "poor" concrete condition as a zone with reduction in unit weight of greater than 3SD from the mean (M). These criteria are based on the statistical observation that a cps data set approximates a standard normal distribution probability function in which 99.7% of the data is within M±3SD. Therefore, when data points are identified beyond 3SD, they represent anomalous zones. While this criterion is generally accepted to define flaws, The

Figure 1.12 Gamma-Gamma Density Logging Equipment. (AMEC Earth & Environmental, Inc.)

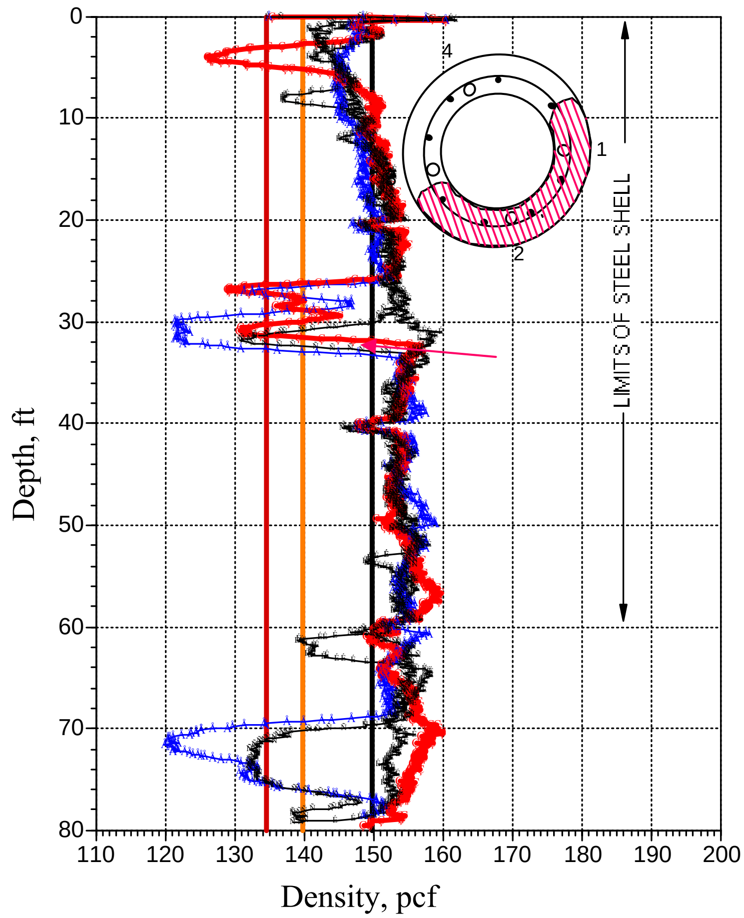


Figure 1.13 Gamma-Gamma Density Logs and Results. (Geophysics, 2002)

computation procedures used by different testers for computing the M and SD is inconsistent. Some compute M and SD based on data from one tube, while others may define these quantities based on data collected from all tubes within a shaft, or all tubes from a group of shafts that may form a single overall foundation element for a superstructure. Obviously, the concrete soundness evaluation may vary based on which method was used in computing M and SD.

1.3.4 Crosshole Sonic Logging (CSL)

The most commonly used drilled shaft foundation down-hole integrity test is cross-hole sonic logging (CSL), also known as ultrasonic testing (ASTM D6760-02). The cross-hole sonic logging technique is an indirect, low strain, non-destructive imaging method for detecting defects inside the rebar cage of a drilled shaft or diaphragm wall element. CSL has become a standard test within most of the USDOT and FHWA, and is currently performed on most drilled shaft in the United States and other developed countries. Prior to the acceptance of CSL, quality assurance testing in the United States was performed only on a very limited number of drilled shafts primarily using the sonic echo and impulse response test. Gamma-gamma density logging tests are gaining popularity as backup tests to CSL for defect identification. Several variations of the CSL equipment and techniques exist, including a source (pulse transmitter) and a receiver simultaneously lowered in the same tube (single hole ultrasonic test, dubbed "SHUTT"), a source and a receiver lowered in adjacent tubes, and a source and multiple receivers lowered in separate tubes. The single source and receiver in adjacent tubes is the most commonly used today. CSL has gained credibility based on tests that were successfully conducted in the United States on hundreds of shafts with depths up to 120 m (tested in China).

1.3.4.1 CSL Basic Theory

The CSL method is a "derivative" of the ultrasonic pulse velocity test. The basic principle of the CSL test is that ultrasonic pulse velocity through concrete varies proportionally with the material density and elastic constants. A known relationship between fractured or weak zones and measured pulse velocity and signal attenuation is fundamental for these tests. Research has shown that weak zones reduce velocities and increase attenuations. During CSL measurements, the apparent signal travel time between transmitter and receiver are measured and recorded. By measuring the travel times of a pulse along a known distance (between transmitter and receiver), the approximate velocity can be calculated as a function of distance over time. If a number of such measurements are made and compared at different points along the concrete structure, the overall integrity of the concrete can be assessed.

The first-arrival travel times (FAT) recorded during CSL testing are known as compressional, primary, longitudinal, or P-wave arrivals. The P-wave is the wave having discrete particle motion in the same direction, as the wave is moving. The surface of the constant phase, or the surface on which particles are moving together at a given moment in time, is called the wavefront. An imaginary line perpendicular to the wavefront is called a ray path. It is often assumed that a beam of produced ultrasonic energy travels along the ray path (Robert E. Sheriff and Lloyd P. Geldart, 1995). Basic elements of the emitted wave during CSL testing are presented in Figure 1.14. The following are definitions of terminology used with CSL analyses (Robert E. Sheriff, 1978):

- wavelength (λ) - distance between successive repetitions of a wavefront,
- amplitude (A) maximum displacement from equilibrium,
- period (T) - time between successive repetitions of a wavefront,
- frequency (f) - number of waves per unit time,

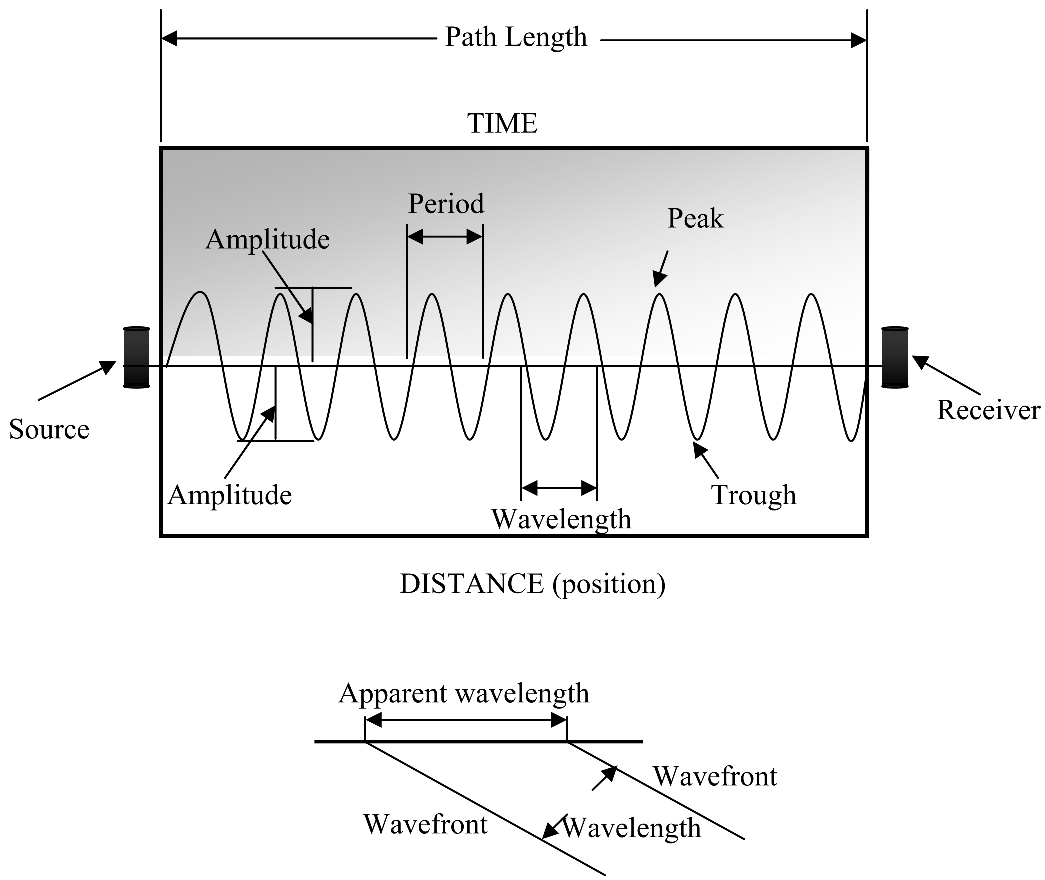


Figure 1.14 Basic Wave Elements

- velocity (V) - speed at which a seismic wave travels, proportional to the frequency and wavelength ($V=f\lambda$),
- apparent wavelength distance between successive similar points on a wave measured at an angle to the wavefront,
- apparent velocity product of frequency and apparent wavelength.

Velocity of the P-wave in homogenous "isotropic" media is related to the modulus and density of the medium through which the wave travels, and is given as:

$$Vp = \sqrt{\frac{(4/3\mu + k)}{\rho}}, \tag{1.3}$$

where

Vp - velocity of the P-wave

μ - shear modulus of the medium through which the wave travels,

k - bulk modulus of the medium through which the wave travels,

ρ - density of the medium through which the wave travels.

$$k = \frac{E}{3(1-2\nu)} \tag{1.4}$$

$$\mu = \frac{E}{2(1+\nu)}, \tag{1.5}$$

where

ν is Poisson's ratio of the medium.

The P-wave velocity can then be written as:

$$Vp = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}}\,, \tag{1.6}$$

where

E - dynamic elastic modulus or Young's modulus

During CSL analysis, the first arrival times of the P-wave are picked using an automated picker within the CSL software, and the pulse velocity can be calculated as:

$$PulseVelocity = \frac{PathLength}{TransitTime} \tag{1.7}$$

For accurate results, it is recommended that the path lengths and transit times be measured with a precision greater than 1%. Although pulse velocity varies with different concrete mixes, the average pulse velocity of a typical concrete is approximately 4,000 m/s. Knowing the linear distance between the transmitter and receiver (path length), and the pulse transit time (first arrival time of the P-wave), the pulse velocity can then be calculated. If the CSL access tubes are not installed in a near vertical position and the distance between them varies significantly along the length of the shaft, errors in velocity calculations may occur, and the results may be misleading.

The seismic wavelength can be calculated based on the known frequency of the transmitted signal and the calculated pulse velocity as shown in Table 1.1. Table 1.1 suggests that the higher the transmitted frequencies used during CSL testing, the shorter the wavelength, allowing for the detection of smaller defects. However, the tradeoff is that the higher the source signal frequency, the greater the signal absorption[1] and the shorter the wavelength. This implies that if higher frequencies are used during the CSL testing, more accurate detection of small defects is permitted, but signal absorption will also be high, limiting the penetration range of the method. Although most CSL systems operate at 35 kHz, frequencies in the range between 30 kHz and 90 kHz are used for CSL tests. At frequencies of about 90 kHz, the wavelength is at about the size of the aggregate. At this scale, the concrete can no longer be considered a homogeneous material. Therefore very high frequencies are not recommended.

Table 1.1 Numerical Relationship between Path Length (PL), Transit Time (TT), Frequency (f), Period (T=1/f), Velocity (V=PL/TT), and Wavelength (λ=V/f)

PL, (m)	TT x10^{-4}, (s)	1/f, (kHz)	1/f x10^{-5}, (s)	V=(PL/TT), (m/s)	λ = (V/f), (m)
0.6	1.6	35	2.8	3,750	0.1
0.6	1.6	50	2.0	3,750	0.075
0.6	2.4	35	2.8	2,500	0.071
0.6	2.4	50	2.0	2,500	0.05

The energy of an ultrasonic wave is a measure of the motion of the medium as the wave passes through it. Energy per unit volume is called energy density (Robert E. Sheriff and Lloyd P. Geldart, 1995). A wave passing through a medium possesses both kinetic and potential energy. Because the medium oscillates as the wave passes through it, energy is converted back and forth from kinetic to potential forms, but the total energy remains fixed. When the particle has zero displacement, the kinetic

[1] Absorption is the process responsible for the gradual and sometimes complete disappearance of wave motion. The elastic energy associated with wave motion passes through the medium, becoming slowly absorbed and transformed into heat (Robert E. Sheriff and Lloyd P. Geldart, 1995).

energy is maximum and potential energy is zero. Conversely, when maximum displacement of the particle occurs, the kinetic energy is zero, and the total energy is all potential energy. When the total energy equals the maximum value of the kinetic energy, the energy density for a harmonic wave is proportional to the first power of the density of the medium, and to the second power of the frequency and amplitude as shown in the following equation:

$$E=2\pi^2\rho f^2A^2 \tag{1.8}$$

where

E = total energy

ρ = density

f = transmitted frequency

A = wave amplitude

1.3.4.2 CSL Applications/Limitations

Cross-hole sonic logging methods are the most conclusive non-destructive geophysical methods available for evaluating the integrity of newly constructed concrete drilled shaft foundations, slurry walls, and seal footings. This method provides information about the material in the zones directly between the access tube pairs, but cannot provide information about material outside those zones or below depths at which the probes were lowered. The soil/concrete interface cannot be evaluated from CSL data. CSL testing is applicable for large-diameter piers of practically unlimited lengths.

Since the typical distances between the access tubes of a pier are relatively short, the travel path of the pulse emission will also be short. Consequently, there is no significant loss of signal energy because of absorption, and higher frequencies (40 to 50 kHz) may be successfully used to obtain higher resolution.

CSL is a popular method in urban areas because of the minimal environmental impact (such as noise, vibrations, or radiation effect) on the test area. Also, this test provides a means to determine the quality of concrete placed in a deep foundation without unnecessary disturbance to the surrounding soil, rebar cage, or to the drilled shaft itself.

Before a CSL test can be performed, the access tubes must be properly installed prior to concrete placement. The tubes must be free of obstacles and must retain water throughout the testing period. The water provides coupling of the sonic probes to the structure. The drilled shaft can be tested between 2 and 40 days after concrete placement if steel access tubes are used, and 2 to 10 days if schedule 40 PVC tubes are used. Access tube debonding may occur after 40 day for steel tubes and after 10 days of concrete placement for PVC tubes, preventing wave transmission through the concrete. If this occurs, the shaft cannot be tested in that tube. In special cases where the drilled shaft diameter is large and retardants are used, it is not recommended to test the piles before 4 days. In certain cases, drilled shafts with steel piles have been tested several years after installation without signs of de-bonding.

The number of tubes required is determined by the diameter of the drilled shaft. Various recommended shaft diameters are shown in Table 1.2. For existing shafts, coreholes must be drilled to allow access for the CSL transmitter and receiver.

1.3.4.3 CSL Testing Equipment

Although many systems are commercially available, AASHTO have not standardized CSL test equipment. Most systems available consist of a pair of hydrophones attached to separate coaxial cables and a data acquisition system. The coaxial cables are either pulled manually or with a motorized winch to control the rate at which the probes are pulled. For the purpose of this report, a brief discussion on the most commonly used systems will be presented.

Table 1.2 Recommended Number of Access Tubes Versus Shaft Diameter (Olson Engineering, Inc.)

Shaft Diameter (D)	Number of Tubes	Tube Spacing, degrees
D ≤ 2.5ft (0.76 m)	2	180
2.5 (0.76 m) < D ≤ 3.5 ft (1.07 m)	3	120
3.5 ft (1.07 m) < D ≤ 5.0 ft (1.52 m)	4	90
5.0 (1.52 m) < D ≤ 8.0 ft (2.43 m)	6	60
8.0 (2.43 m) <D	8	45

Olson Engineering – CSL System

The CSL-1 and CSL-2 systems built by Olson Engineering, Inc., are PC-based analog systems designed for detecting defects in concrete drilled shafts and slurry walls using one or more receivers in boreholes. The receivers are electronically bandpass filtered around their resonant frequency to reduce noise. A single transmitter and a single receiver are used with the CSL-1 system, and a single transmitter with multiple receivers (hydrophones) is used with the CSL-2 system. The CSL-2-system reduces test time dramatically, especially if collecting multiple sets of offset data for tomography. In both systems, the probes are pulled to the surface over a wheel counter to control speed and accurately measure probe location within the 50 mm diameter access tubes. The logging rate of the CSL-1 system permits complete testing of a 30 m deep pair of tubes with 500 test records in about four minutes with two persons, and in less than eight minutes for one person. The CSL-2 option provides a second hydrophone receiver to permit simultaneous logging of two tube pairs, allowing faster testing of large shafts and diaphragm walls. All data are recorded onto the Freedom NDTPC hard drive, permitting review of individual records. The raw data are typically archived on magnetic media for long-term data storage after analysis and printing of results. A typical system setup is shown in Figure 1.15. The systems have the following features:

- Ease of data collection and analysis with the portable, battery powered, Freedom NDTPC.
- Ruggedized, lightweight, and water resistant.
- Optional tomographic imaging software available.
- Ability to review all signals immediately following the tests and to archive on tape or disks.
- Ability to output results to a printer for quick field use.
- Provides immediate on-screen field results with graphical presentation of signal time, velocity, and/or energy.
- On-screen cursors to allow precise definition of defect depth and severity.
- State–of–the-art design provides extended testing distances up to 8-m-diameter shafts (less resolution of defects for longer paths).
- One or two person operation.
- Internal 12 volt DC battery powered, or external 12 volt DC (car) or automatic 90 – 260 volt AC power source flexibility.
- Capability of displaying results in both metric and English units.
- CSL-1 system for single log or CSL-2 system for multiple simultaneous logs simultaneously.

Specifications for the Freedom NDTPC

- Pentium Single board computer (SBC) (486 option available) 16 or 32 Megabytes of Ram.

Figure 1.15 Freedom NDTPC Family of Instruments (Olson Engineering, Inc.)

- Aluminum chassis with two module bays in a high-impact sealed plastic instrument case.
- 2.1 Gb hard drive and 1.44 Mb floppy drive.
- 2 serial COM ports and 1 parallel port.
- Transflective LCD Monochrome 9.4 in diagonal display VGA (640 X 480), excellent in sunlight, and backlit for nighttime viewing with output for external SVGA monitor.
- Color Screen Option.
- LED battery condition indicators.
- DOS Operating System/Windows option available.
- 86 key removable keyboard with cover.
- 1 MHz Data Acquisition 12 bit A/D Card.
- ISA Back-plane with 4 slots (2 full-length open slots).
- 1 – half-length slot for SBC.

- 1 – full-length slot for A/D Card.
- An (FAA approved) 13.5 lb (6.1 kg) sealed rechargeable/removable battery set.
- Built-in connector for internal modem or LAN.
- Freedom NDTPC Size is 18.5 inches x 14.74 inches x 7.5 inches (47x37x19 cm).
- 35 lb (16 kg) with batteries (standard system).

Other system options

- 486 and 686 Single Board Computers.

- SBC with PCI/ISA Backplane (1 PCI, 1 PCI/ISA combo, 2 ISA full length).
- 1 – 2/3-length open PCI slot.
- 1 – Combo ISA/PCI full-length slot for SBC.
- 1 Full-length ISA slot for data acquisition card.

- LCD color VGA display.
- Automobile power interface cable.
- Additional rechargeable battery set with charger.
- Additional memory.
- Larger capacity hard drive.
- Touch pad mouse.
- Internal modem.
- Windows 95/Windows NT.
- Six current NDE modules available.
- Custom modules designed per customer specifications-not limited to NDE.

Standard power supply

- External AC/DC power converter (90 – 260 volt AC input, 15 volt DC output).

- Sealed rechargeable battery set (FAA approved).
- Standard system has a running time of approximately 8-9 hours on internal batteries.

PILELOG - CSL System

The full-waveform cross-hole sonic system is designed for logging of drilled shaft foundations, slurry walls and dams between water-filled plastic or steel tube pairs. The PILELOG system shown in Figure 1.16 offers in situ characterization of placed concrete displaying the data in either color or gray-scale full-waveform "concrete sonogram" output. Unlike other systems, this system improves downhole-logging technology by providing downhole probes with on-board A/D cards, amplifiers and filter circuitry, multiplexers, source drivers, and modems. This allows the signal to be digitized at the probe and transmitted with very limited interference from electrical or magnetic noise.

<u>General features</u>

- Automated winch system for fast and accurate logging of the shaft.
- Downhole digitization with 12-bit resolution.
- Use of full waveform sonic logging software for a full "Sonogram" display.
- Use of any standard 386 or better portable computer for the display and control of the system.
- Centering tool to minimize mechanical pull noise resulting from probes bumping on the side of the tube.
- Ultra-portable design with ruggedized waterproof chassis.
- Technical specifications as summarized in Table 1.3.

Figure 1.16 PILELOGs – Full Waveform Cross-hole Sonic Logging System (InfraSeis, Inc.)

Table 1.3 Technical Specification for the PILELOG - CSL system

Probe OD	3.5 cm	**Probe length:**	0.5m
Winch:	Tripod with dual split drum 61 – 122 m	**Depth Interval:**	5 cm with 2 independent depth measuring system
Logging Speed:	Variable, up to 12 m/min	**Frequency of Sonic Wave:**	38 kHz
Sampling Rate:	Programmable, maximum 2μ sec	**Samples Per Trace**	Programmable, up to 1024 samples
Dynamic Range:	12 bits plus configurable gain	**Transducers:**	Piezo-electric transmitter/receiver
Shipping Weight:	31.75 kg	**Voltage:**	110/220 V

CHUM - CSL System:

The CHUM system is an instrument for testing piles using the ultrasonic method. The CHUM equipment is shown on Figure 1.17. This system does not utilize a constant speed winch for pulling the probes during the testing. The operator monitors the probe movement on the screen.

General features

- Perform quality control on bored piles, drilled shafts, slurry wall elements, and barriers.
- Detect anomalies as small as 10 cm (resolution depends various conditions).
- Determine the exact depth of these anomalies.
- Perform real-time tomography to determine the size and location of anomalies.
- Perform single-hole ultrasonic tests.

Figure 1.17 PISA – Pile Integrity Sonic Analyzer (Geosciences Testing and Research, Inc.)

<u>General specifications</u>

- *Performance*: up to 4 m diameter in good quality concrete.
- *Cable length:* 50 m (standard), 100 m (optional).
- *Depth wheel:* one bi-directional Omron E6A2-CW3C, 100 pulses per revolution (standard), additional bi-directional depth meter enabling real-time tomography (optional).
- *Output:* Arrival time and energy/attenuation curves, dual presentation, “waterfall” presentation, fuzzy-logic tomography and parametric tomography, all in either black and white or color. Report generation in Windows – based word processing format.
- *Software*: Windows–based, optimized for pen control, automatic determination of first arrival time, automatic gain control.

Table 1.4 Transducers Specifications

<u>**Transducers specifications:**</u>	**Transmitter**	**Receiver**
Ceramic element Probe length: 250 mm Diameter: 25 mm Frequency: 50 kHz Probe weight~ 200 g	Max voltage: 250 V Max pulse repetition rate: 40 Hz Charge circuit: 22 ohm, 2μF	Power supply: 12 V Impedance: 50 ohm

1.3.4.4 CSL Test Procedures and Results

CSL testing can be performed on either drilled shaft foundations or pre-cast concrete piles, provided that 50-mm-diameter steel or PVC access tubes capable of holding water are installed (50-mm-diameter holes can be cored, if necessary). These tubes must extend at least 1 m above the top of the shaft to compensate for water displaced by insertion and removal of the transmitter, receiver, and cable. To reduce the chances of tube debonding, steel access tubes are preferred (steel tubes are not suitable if SHUT is to be applied). If schedule 40 PVC tubes are used, the tests must be performed within 10 days after concrete placement to avoid debonding at the PVC/concrete interface. Other factors may also cause debonding:

1) Disturbance of tubes during or shortly after concrete placement.
2) Improperly tying the tubes firmly to the cage.
3) Delays in filling the tubes with water.

To perform CSL testing, two probes, a piezoelectric transmitter, and a receiver are lowered to the bottom of two access tubes. These probes are simultaneously pulled vertically at a constant interval while pulses are created and recorded. During testing, the transmitter and receiver are maintained at the same elevation to create a horizontal signal travel path between the transmitter and the receiver. The cables to the probes pass through a meter-wheel that is connected to the data acquisition control unit. The meter-wheel controls the ultrasonic wave pulse by triggering the pulse generator at predetermined vertical intervals, causing the transmitter probe to emit an ultrasonic pulse. The timer circuit measures the time between pulse emission and subsequent detection by the receiver. Since the number of pulses emitted is a function of meter-wheel rotation and the wheel circumference is known, the depth of the probes can be calculated. All records are automatically stored on the system hardware.

In general, the range of frequencies used for concrete testing is between 20 kHz and 250 kHz, with 35 kHz being most commonly used for field-testing of drilled shafts. Since concrete is a heterogeneous material, high-frequency pulses (short wavelengths of energy) are unsuitable for use because of the considerable amount of energy attenuation. The corresponding wavelength is approximately 200 mm for lower frequencies (20 kHz) and approximately 16 mm for the higher frequencies (250 kHz).

The waveform of the raw data is digitized and continuously displayed with the positive peak of the received pulse presented and the negative peak displayed as blank space. In some CSL systems, the full waveform traces are stacked and displayed in a format representing vertical profiles of the pulse propagation time through the concrete (dubbed "waterfall" profiles) as shown in Figure 1.18(a). Other logs depict the arrival times, apparent velocity, and energy amplitude versus depth, as shown in Figure 1.18(b).

CSL results can be evaluated on-site immediately following testing. Concrete integrity can be preliminary assessed based on first arrivals and signal amplitude. Good quality concrete is indicated by constant travel time per unit distance and good signal amplitude. Where the pulse velocity is reduced by defects or low modulus material, the propagation time will be longer, and the amplitude will decrease. Several irregularities can be identified at different locations within the same-drilled

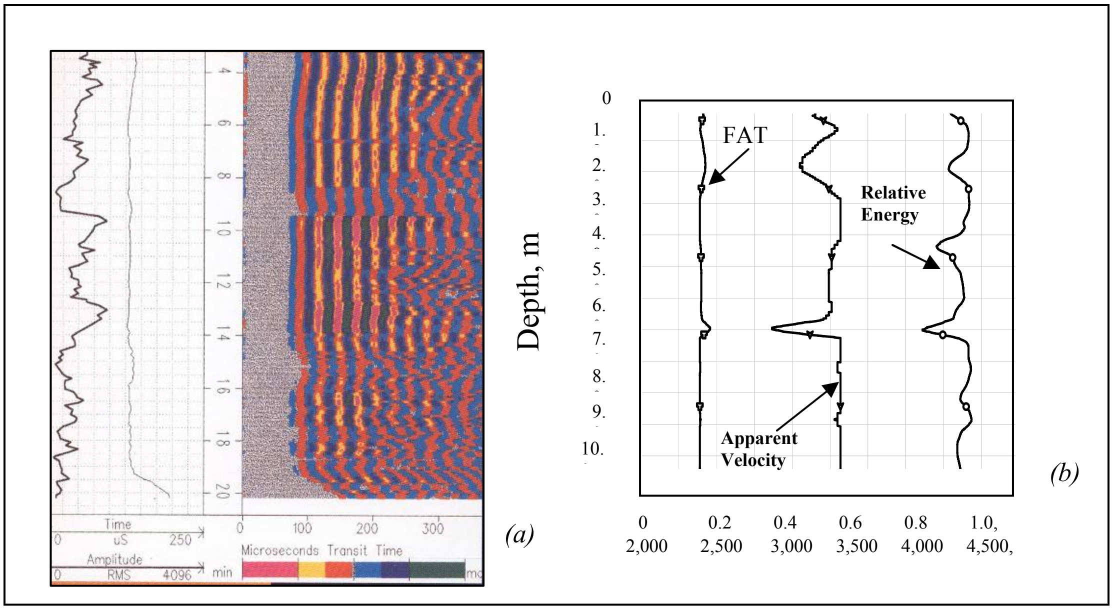


Figure 1.18 (a) Full Waveform Stacked Traces (InfraSeis, Inc.) and (b) CSL Log Plot –First Arrival Time (FAT), Apparent Velocity and Relative Energy Versus Depth (GRL & Assoc., Inc.)

shaft as shown in Figure 1.19. In some cases, defects can significantly reduce pulse amplitude, causing the signal to be lost completely. Poor bonding between access tubes and the concrete, or de-lamination, can also cause complete signal loss. Steel tubes provide improved bonding with concrete, but the high mechanical impedance of steel may cause attenuation of the signal transmission and the signal may not be as well defined when PVC tubes are used. Since the tubes must be oversized to permit free passage of the probes and to allow for minor bending of the tubes during placement, the probes are somewhat free to move laterally. Consequently, this may cause variation in transmitted pulse strength and received signal amplitude.

The received amplitude of an ultrasonic pulse can also vary depending on aggregate shape, orientation, and local changes in aggregate distribution. Concrete defects such as gravel zones, soil inclusions, bentonite inclusions, or honeycombing have a much

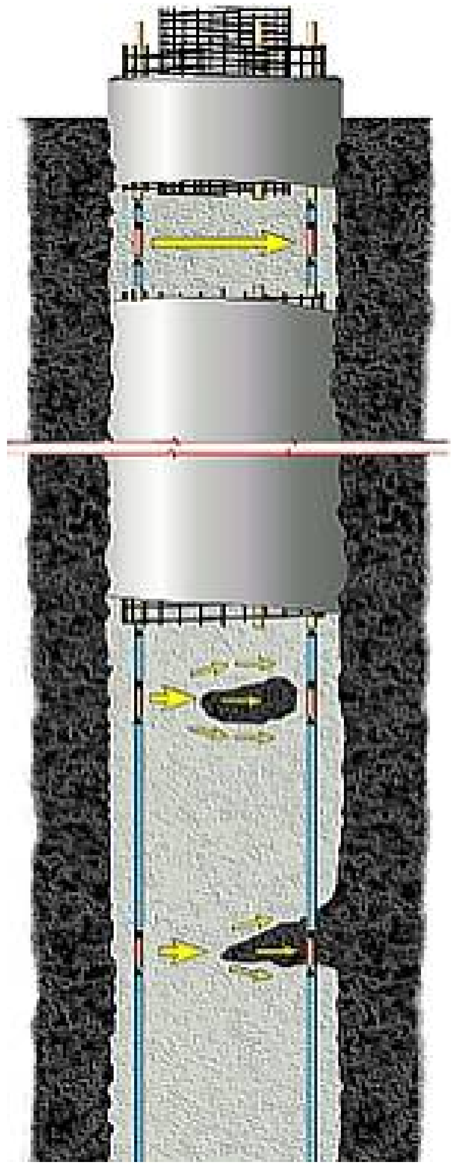


Figure 1.19 Drilled Shaft with Defects

lower propagation velocity, and their presence can usually be detected.

Current CSL tests only indicate that an anomaly may exist somewhere between two access tubes. It is, however, difficult to determine the geometry and exact location of the anomaly with the respect to tube location. To better characterize defects in terms of size, geometry, and location, additional CSL tests are performed. Data are collected with several offsets between transmitter and receiver in adjacent boreholes and used for detailed analysis and cross-hole tomography. A 2-D color tomogram is then plotted to better identify anomaly geometry and location.

1.3.5 Other Specialized Logging Methods

Other geophysical logging probes can be used to assess the condition of in-place concrete. This includes temperature logging and neutron logging for evaluating concrete curing conditions, and for measuring moisture content respectively. Electrical and ground penetrating radar (GPR) logging can also be used for examining the condition and positioning of rebar within the cage.
In the next section, a brief description of neutron-moisture logging (NML) and the temperature logging will be presented.

1.3.5.1 Neutron Moisture Logging (NML)

In the neutron-moisture logging (NML) method, an americium-beryllium neutron source in sizes of 1- to 5-curies source is used to emit high-energy neutrons into the surrounding material. Helium-3 detectors are used to record the interactions that occur in the vicinity of the access tubes. Two different neutron-logging techniques can be used: 1)- geophysical neutron probes with a large source size (>1 curie) and long spacing (>30 cm) with radius of investigation of about 15-18 cm and, 2)- engineering probes with a small source size (<100 millicuries) and short spacing (<30 cm) with radius of investigation of 2.5-5 cm. Three general types of neutron-porosity logs exist: neutron-epithermal neutron, neutron-thermal neutron, and neutron-gamma. Cadmium foil may be used to shield Helium-3 detector from thermal neutrons. Neutron-epithermal neutron logs are least affected by the chemical composition of surrounded material.

Fast neutrons, emitted by a source, undergo three basic types of reactions with matter adjacent to the access tubes (concrete, steel, and possibly moisture and soil) as they lose energy and ultimately are captured. These physical interactions include inelastic scatter, elastic scatter, and absorption or capture. In elastic scatter, the mass of the scattering element controls the loss of energy by the neutron. Light elements (mostly hydrogen element in water) are most effective in moderating, or slowing neutrons, whereas heavy elements have little effect on neutron velocity or energy. The moderating and capture processes result in the number of epithermal and thermal neutrons and capture gamma photons being inversely related to the hydrogen content of concrete, at source-to-detector spacing greater than approximately 30 cm. If detectors are located closer than 30 cm from the source, as in engineering moisture probes, the number of moderated and captured neutrons increases with increasing hydrogen content.

Typical NML logs are presented in a similar format as GDL logs with measured neutron counts per second (cps) displayed along with the mean and the -2 and the -3 standard deviation from mean vertical guidelines. High moisture zones are indicated by low count rates deflection in the data.

1.3.5.2 Temperature Logging

The temperature logging of concrete can be estimated by measuring the water temperature in the access tubes over time using very sensitive temperature instrumentation. Since the access tubes are generally at the same radial distance from the center of the shaft, no direct measurements of the high central temperature can be measured with this method. Thermocouples can be embedded in the center of the shaft at any elevation to measure the temperature gradient during concrete curing.